

GEANT4 simulation of the characteristic gamma-ray spectrum of TNT under soil induced by DT neutrons*

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The characteristic gamma-ray spectrum of TNT in the soil induced by DT neutrons is measured by the PFTNA demining system. The GEANT4 toolkit is used to simulate the whole experimental procedure. The simulated spectra are compared with the experimental spectra, and they are mainly consistent. The share of the background sources such as neutrons and gamma is obtained and the contribution that the experimental apparatus to the background, such as shielding, detector sleeve and moderator, is analyzed. The effective gamma signal (from soil and TNT) is 29% of the full spectrum signal, and the background signal, more than 68%, this is mainly produced by shielding and the detector sleeve. By gradually optimizing the shielding and the cadmium sheet of the detector sleeve, the share of the effective gamma signal increases to 47%, and the background signal reduces to 18%.

Keywords: GEANT4, Neutron induced, Characteristic gamma-ray spectrum, Background contribution

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I. INTRODUCTION

Research on explosives detection has gotten more attention around the world in terrorist activities in recent years. The traditional neutron activation analysis (NAA) [1] method has difficulty distinguishing explosive and non-explosive organic materials because of the same components of C, H, N, and O. The pulsed fast/thermal neutron analysis (PFTNA) [2] technique can combine the prompt inelastic scattering gamma-ray spectrum of fast neutrons with the delayed radiative capture gamma-ray spectrum of thermal neutrons. Both spectra contain the characteristic gamma-ray spectrum of the four elements. When utilizing different characteristics of the gamma-ray spectrum, it is possible to identify the contents of these elements and distinguish explosive or non-explosive species. The PFTNA technique has been widely used in industrial production due to its high sensitivity and accuracy, such as analyzing coal composition [3, 4]. Also, the PFTNA technique can be used to analyze the content and ratio of H, C, O and N in the detection of mines and other explosives, especially non-metallic mines. However, the explosives have different structures in complicated environmental conditions. At present, the PFTNA technique is mainly focused on the theoretical and experimental exploration. Some actual probes are carried out in a few countries and regions [5–7].

When the gamma-ray spectra of mines and explosives are measured by the PFTNA method, many complex signals should be generated, including gamma signals from the target, and the background by neutrons and gamma signals, the experimental apparatus and the environment. However, in an experiment the detector cannot distinguish the type and source of all signals. The composition of the spectrum, the

contribution of experimental apparatus to the background can be obtained by GEANT4.

In the present work, the characteristic gamma-ray spectra of TNT in the soil induced by DT neutrons are measured by the PFTNA demining system. The GEANT4 toolkit is used to simulate the whole experimental procedure, and the simulated are compared with and experimental those, to obtain background sources such as neutrons and gamma. The contribution of experimental apparatus to the background, such as the shielding, detector sleeve, and moderator, is analyzed.

II. INTRODUCTION OF EXPERIMENTAL PLATFORM

The experiment was completed in the Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics. The 14 MeV fast neutrons were produced by a pulsed D-T neutron generator at pulse width of 80 μ s and pulse interval of 50 μ s, and used to irradiate TNT. The pulsed neutron generator was a cylinder with 9.8 cm diameter, can reach about 10^7 – 10^8 /s yield, and the target was centrally away from 20 cm at its front. Neutrons launch from the target in the direction of 4π . Outside of the neutron generator, there is a layer of a polyethylene moderator [8]. TNT (2 kg) was located in the center of soil sizes of 5 m \times 5 m \times 1 m at a depth of 2 cm. A LaBr₃(Ce) detector with the size of ϕ 7.5 cm \times 7.5 cm is used to obtain prompt inelastic scattering gamma-ray spectrum of fast neutrons and the delayed radiative capture gamma-ray spectrum of thermal neutrons. There was a sleeve with a size of ϕ 150 mm \times 135 mm outside of the detector, and its outer layer was 1 mm iron, and the inner layer is 5 mm lead. On the bottom of the sleeve, there was cadmium sheet with 2 mm thickness. To reduce its radiation damage due to neutrons A 60 mm-thick lead block was alternated with 200 mm-thick polyethylene and a 80 mm-thick lead block was used to shield the detector. The experimental arrangement is shown in Fig. 1.

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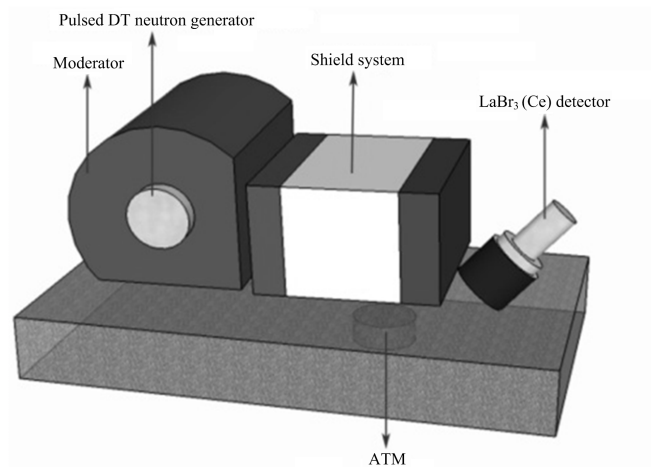


Fig. 1. The experimental arrangement.

III. SIMULATED RESEARCH METHOD

The GEANT4 toolkit [9, 10] was used to simulate the whole experimental procedure based on the structure and size of the experimental apparatus. Fig. 2 shows that the apparatus contours given by GEANT4 is fundamentally consistent with the experimental apparatus. After 14 MeV neutrons hitting the TNT, the energy deposition measured by the $\text{LaBr}_3(\text{Ce})$ detector was simulated. By recording the global time and physical process for each energy deposition, the simulated fast neutron and thermal neutron induced spectra were compared with experimental those.

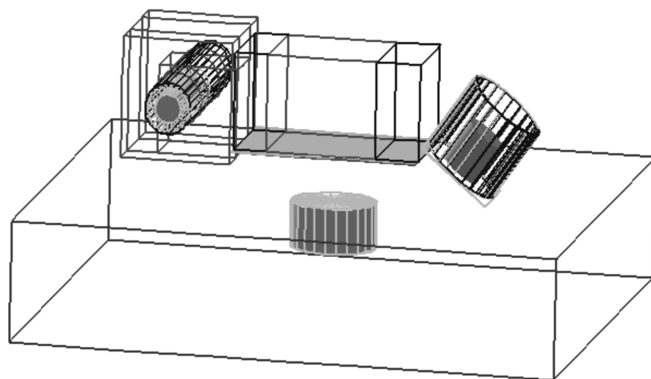


Fig. 2. Contours of the apparatus given by GEANT4.

Each energy deposition produced particles was simulated, and the deposited energy, the area and the primary radiation were recorded by the detector, thus obtaining the share of the background sources, such as neutrons and gamma. Further, the contribution of shielding, the detector sleeve and the moderator to background can be obtained. The background can be reduced by improving the experimental apparatus.

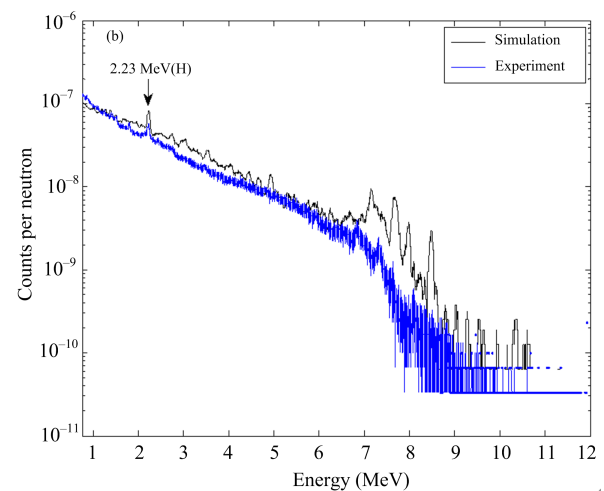
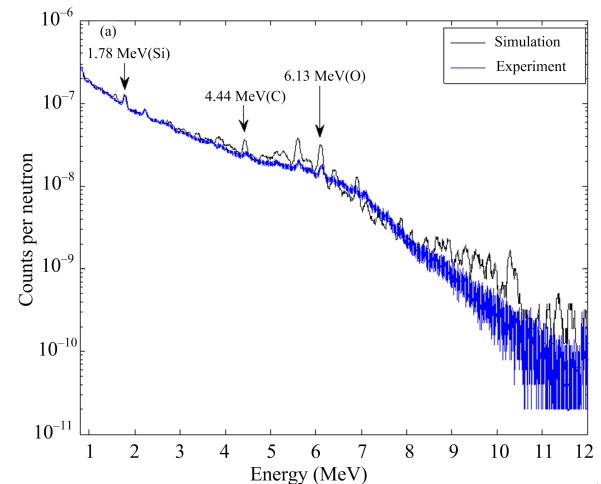


Fig. 3. (Color online) Comparisons between experimental and simulated fast spectra (a) and experimental and simulated thermal spectra (b).

IV. RESULTS AND DISCUSSION

A. Comparison between simulated and experimental results

Figure 3(a) shows the experimental and simulated fast neutron induced spectrum (fast spectrum) of the TNT. Fig. 3(b) shows the experimental and simulated thermal neutron induced spectrum (thermal spectrum). Comparatively, the experimental spectra are folded with an energy resolution due to the statistical fluctuation of the number of carriers, the noise of the detector, and electronic system. The simulated spectra are consistent with the experimental those except Gaussian broadening, the broadening coefficients are obtained by fitting the experimental data. Also, Fig. 3 shows that experimental spectra are consistent with simulated in the low-energy region of the fast spectrum, the peaks of the simulated spectra, however, are more obvious in the high-energy region. The main reason is that the TNT is buried in the soil in the experiment, and it is difficult for its com-

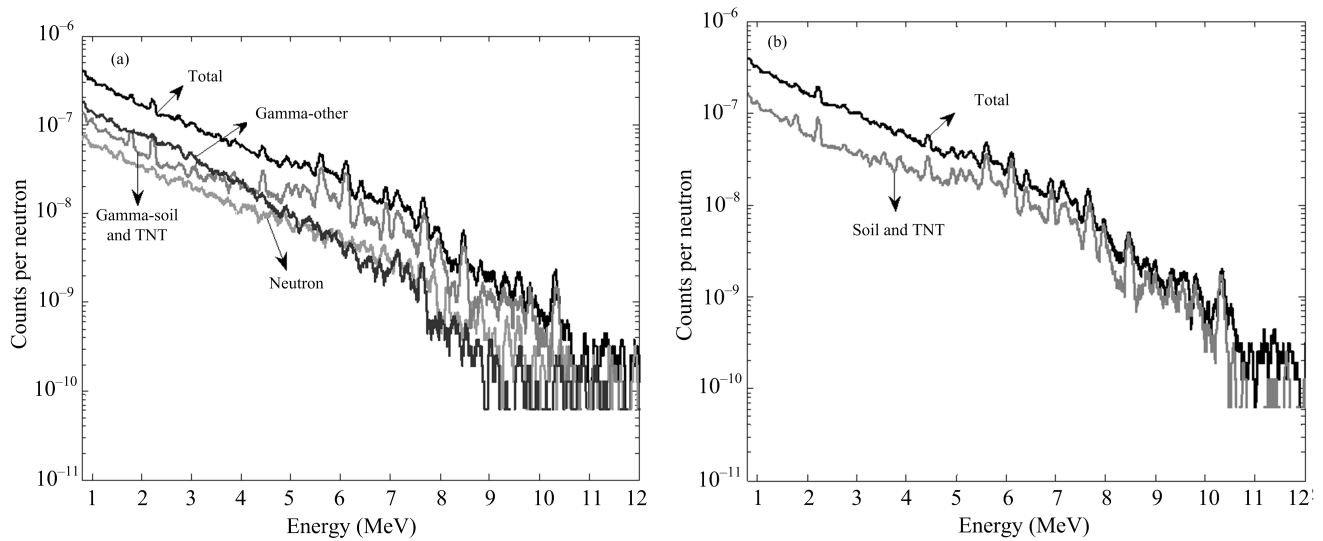


Fig. 4. Analysis of the spectra of TNT in the original structure.

plex composition to be analyzed quantitatively. Differently, the simulated soil contains only 62% SiO_2 , 25% Al_2O_3 , 3% Fe_2O_3 , 10% H_2O . Each channel of the high-energy region (8–12 MeV) in the simulated spectra has only a few counts. In Fig. 3, the Y-axis counts normalized to each neutron would cause large statistical fluctuation. When doing Gaussian broadening, false peaks are formed in this energy interval, meaning that counts are not reliable in this region of the simulated spectra. In Fig. 3(a), we can clearly see the $^{16}\text{O}(\text{n}, \text{n}'\gamma)^{16}\text{O}$ ($E_\gamma = 6.13$ MeV), $^{12}\text{C}(\text{n}, \text{n}'\gamma)^{12}\text{C}$ ($E_\gamma = 4.44$ MeV), and $^{28}\text{Si}(\text{n}, \text{n}'\gamma)^{28}\text{Si}$ ($E_\gamma = 1.78$ MeV) gamma-ray full-energy peaks and parts of their escape peaks, and the $^1\text{H}(\text{n}, \gamma)^2\text{D}$ ($E_\gamma = 2.23$ MeV) gamma-ray full-energy peak in Fig. 3(b). Because the cross section of the radiative capture reaction between thermal neutrons and the N element is small and the share of thermal neutrons is small, the $^{14}\text{N}(\text{n}, \gamma)^{15}\text{N}$ ($E_\gamma = 10.83$ MeV) gamma-ray full-energy peak is nearly absent in Fig. 3(b).

B. Analysis of simulated spectrum

Based on the simulation method described above, the full spectrum of the TNT is analyzed, as shown in Fig. 4. The left figure shows that the four spectra are produced by all particles (Total), neutrons (Neutron), gamma photons from the soil and TNT (Gamma-soil and TNT), and gamma photons outside of the soil and TNT (Gamma-other), including the sleeve outside of the LaBr_3 detector, shielding devices, and the moderator outside of the neutron generator, and others. On the right figure, the “Total” spectrum is produced by all particles; and the “Soil and TNT” spectrum, by particles from the soil and TNT.

Analyzing the full spectrum signal shows that its background is too large, because the gamma signal from the soil and TNT is only 29%, the background signal from neutrons

is 31%, and the background signal from the gamma photons outside of the soil and TNT is 37%. Therefore, the background needs to be reduced by improving the experimental apparatus.

C. Improvement of experimental apparatus

After studying the background sources, it was found that a significant contribution of the cadmium sheet on the bottom of the sleeve outside of LaBr_3 detector to the background. In addition, the shielding placed between the detector and the DT neutron source has a limited effect on stopping neutrons, thus meaning that a larger portion of neutrons can traverse the detector through the shielding. Table 1 shows the contribution of each part of experimental apparatus to background.

From Table 1, the contribution of cadmium of the detector sleeve and the shielding to background is more than 65%. So, improving the design of the cadmium sheet and shielding should increase the signal-to-noise ratio.

1. Improvement of cadmium sheet

Source neutrons can be scattered into the LaBr_3 detector by the environment and absorbed by the cadmium sheet on the bottom of the sleeve, thus reducing the background signal from neutrons. However, gamma-rays will be produced when absorbing neutrons, and lead to an increase of the background signal. The ratio of the effective gamma signal counts (from soil and TNT) to total counts (N_{efg}/N_t) and background signal counts from neutrons to total counts (N_n/N_t) are considered as the targets. By gradually reducing the size of the cadmium sheet, the relationship of N_{efg}/N_t and N_n/N_t vs. the size of the cadmium are obtained, as shown in Fig. 5, to find the optimum size of the cadmium sheet.

TABLE 1. Various parts of experimental apparatus that contribute to background

Parts of experimental apparatus	Cadmium of detector sleeve	Fe and Pb of detector sleeve	Shielding	Moderator	Others
Contribution to background	44.79%	8.21%	21.40%	4.01%	21.58%

TABLE 2. Various parts of experimental apparatus that contribute to background

Material	2 mm cadmium	2 mm lithium
N_{efg}/N_t	29%	42%

From Fig. 5(a), the share of the effective gamma signal increased only 4% up to the thickness of 0.2 mm cadmium, this is due to that the background gamma signals will be produced while the cadmium absorbs neutrons. Therefore, we considered that the 0.2 mm cadmium replaced with 0.2 mmlithium because ${}^6\text{Li}$ does not produce gamma rays and has a high the cross section of reaction. The simulated result is shown in Table 2.

From Table 2, the share of the effective gamma signal improved from 29% to 42% at the 2 mmlithium. Then, because the GEANT4 simulated result shows that the effective gamma signal increased very slowly with the thickness of lithium, 2 mm lithium is replaced with 2 mm cadmium on the bottom of the detector sleeve.

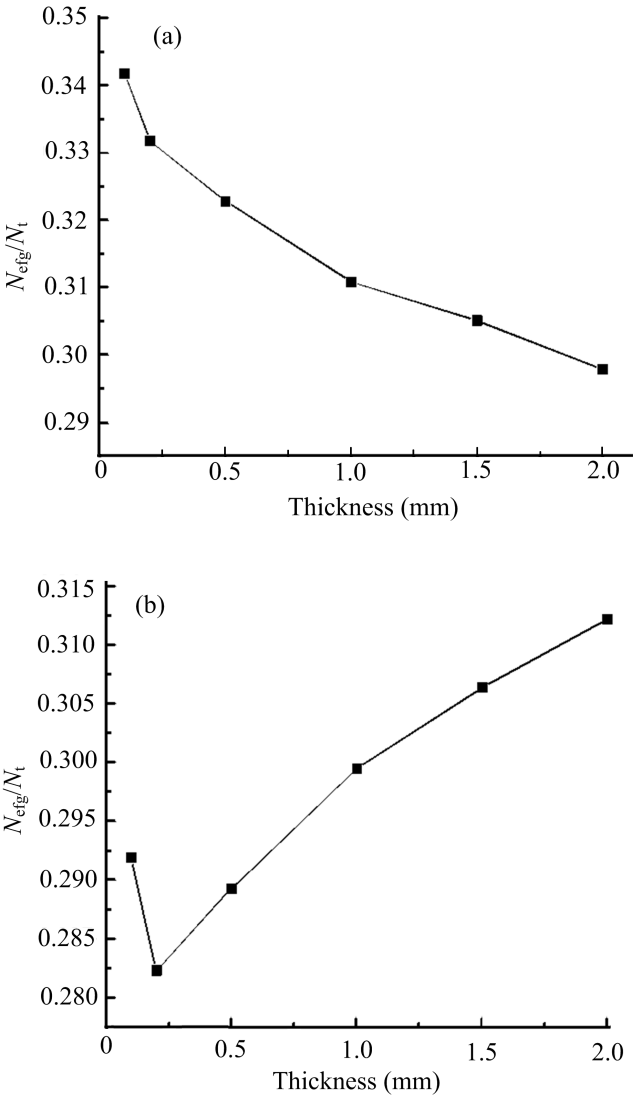


Fig. 5. The relations of N_{efg}/N_t (a) and N_n/N_t (b) with the thickness of sheet cadmium.

From Fig. 5(a) and 5(b), N_{efg}/N_t gradually increased from 29% to 34% with reducing the thickness of the cadmium sheet from 2 mm to 0.1 mm. N_n/N_t first decreased, then increased, and is minimal at 0.2 mm, generating the smallest background signal, and accounting for 28% of the full spectrum signal.

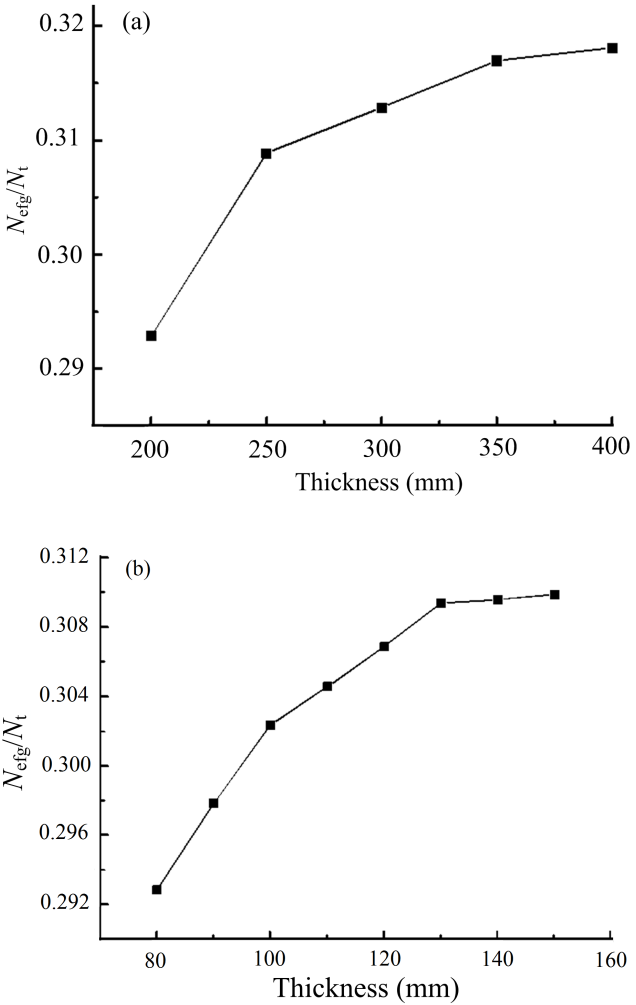


Fig. 6. The relations of N_{efg}/N_t with size of polyethylene (a) and the second layer of lead (b).

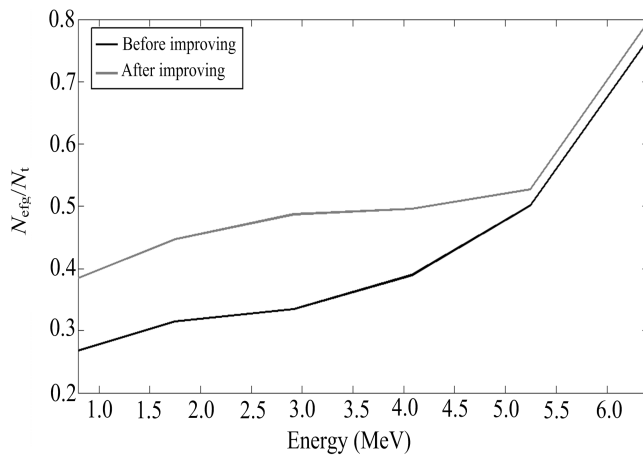


Fig. 7. N_{efg}/N_t changes with the energy of gamma before and after improving the experimental apparatus.

2. Improvement of shielding

The alternating structure of polyethylene layer and lead layer is used to shielding. The lead in first layer can reduce the energy of fast neutrons by inelastic scattering, and the polyethylene moderate them to the thermal neutrons due to being slowed down and absorbed. The lead in second layer is used to absorb gamma rays during the process of moderation and absorption. In this experiment, neutrons must get through a layer of moderator, to generate less background signal in the first lead layer. The simulated result shows that the background signal is mainly produced in the polyethylene and the second lead layer. Therefore, the N_{efg}/N_t increases with thicknesses of polyethylene and the second lead layer, as shown in Fig. 6, thus obtaining their optimum sizes.

From Fig. 6(a), keeping the thickness of the first lead layer of (60 mm) and the second lead layer (80 mm), N_{efg}/N_t increased from 29% to 31% with the thickness of polyethylene from 200 mm to 250 mm. The N_{efg}/N_t increased more slowly with the thickness of polyethylene. Actually, the optimum thickness of polyethylene is 250 mm. From Fig. 6(b), keeping the thickness of the first layer of lead (60 mm) and the polyethylene thickness of 200 mm, N_{efg}/N_t increased from 29% to 31% with the thickness of the second lead layer from 80 mm to 130 mm. The N_{efg}/N_t does not significantly change with the thickness of the second lead layer. Therefore, the op-

timum thickness of the second lead layer is 130 mm.

D. Analysis of spectrum after improving experimental apparatus

Also, the TNT spectrum is simulated and analyzed by improving the experimental apparatus. Fig. 7 shows the ratio of the effective gamma signal counts (from soil and TNT) to total counts (N_{efg}/N_t) changes with gamma energy before and after improving the experimental apparatus. This is only figure of low- to mid-energies because the less counts from the high-energy end of the spectrum creates large statistical error fluctuations. From Fig. 7, N_{efg}/N_t increased after improving the experimental apparatus. The characteristic peaks of H 2.23 MeV, C 4.44 MeV, and O 6.13 MeV have been strengthened and their signal levels have also been improved. In the full spectra, the share of gamma photons from the soil and TNT is up to 47%, increasing by 18% after improving the apparatus, and the background signal from neutrons and gamma photons reduced by 18%.

The characteristic signal of the full spectrum should be improved because the background accounts for more than 50%. Further, shielding structures reducing the neutrons and gamma photons simultaneously should be studied.

V. CONCLUSION

A mixed gamma-ray spectrum is formed by DT neutrons hitting TNT in the soil and simulated by the GEANT4 toolkit. The contribution of different types of particles and their sources to the spectra are studied. The effective gamma signal (from soil and TNT) only accounts for 29%; and the background signal, more than 68%. The cadmium sheet on the bottom of the detector sleeve and the shielding device contribute significantly to background. After replacing cadmium with lithium and improving the size of the shielding, the characteristic peaks are strengthened. The share of the effective gamma signal increased to 47% while the background signal fell to 18%. The contribution and source of the background was performed by using the GEANT4 toolkit, to optimize a reliable experimental device of neutrons.

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- [1] Zhu J, Solbrekken G, Hao W, *et al.* Neutron activation analysis of bulk samples from Chinese ancient porcelain to provenance research. *J Radioanal Nucl Ch*, 2013, **298**: 237–242. DOI: 10.1007/s10967-013-2505-z
- [2] Vourvopoulos G, Womble P C. Pulsed fast/thermal neutron analysis: a technique for explosives detection. *Talanta*, 2001, **54**: 459–468. DOI: 10.1016/S0039-9140(00)00544-0
- [3] Jing S W, Liu LM, Gu D S, *et al.* Coal analysis using the pulsed neutron generator. *Nucl Sci Tech*, 2003, **14**: 265–267.
- [4] Gu D S, Jing S W, Sang H F, *et al.* Detection of low caloric power of coal by pulse fast-thermal neutron analysis. *J Radioanal Nucl Ch*, 2004, **262**: 493–496.
- [5] Gozani T, Elsalim M, Ingle M, *et al.* Gamma ray spectroscopy features for detection of small explosives. *Nucl In-*

- strum Methods Phys Res Sect A, 2003, **505**: 482–485. DOI: [10.1016/S0168-9002\(03\)01141-0](https://doi.org/10.1016/S0168-9002(03)01141-0)
- [6] Vourvopoulos G. Industrial on-line bulk analysis using nuclear techniques. Nucl Instrum Methods Phys Res Sect B, 1991, **56**: 917–920. DOI: [10.1016/0168-583X\(91\)95062-I](https://doi.org/10.1016/0168-583X(91)95062-I)
- [7] Womble P C, Campbell C, Vourvopoulos G, *et al.* Detection of explosives with the PELAN system. AIP Conf Proc, 2001, **576**: 1069–1072.
- [8] Redal A M. Monte Carlo simulations of a D-T neutron generator shielding for landmine detection. Radia Meas, 2011, **46**: 1187–1193. DOI: [10.1016/j.radmeas.2011.07.013](https://doi.org/10.1016/j.radmeas.2011.07.013)
- [9] <http://cern.ch/geant4>.
- [10] Agostinelli S, Allison J, Amako K, *et al.* Geant4—a simulation toolkit. Nucl Instrum Methods Phys Res Sect A, 2003, **506**: 250–303. DOI: [10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)